A liquid xenon PET camera for neuro-science

J. Collot, S. Jan, E. Tournefier

Frascati Physics Series Vol. nnn (2001), pp. 000-000
IX Int. Conf. on Calorimetry in Part. Phys. - Annecy, Oct. 9-14, 2000

A LIQUID XENON PET CAMERA FOR NEURO-SCIENCE

J. Collot , S. Jan , E. Tournefier
Institut des Sciences Nucléaires
IN2P3/CNRS - Joseph Fourier University
53 av. des Martyrs
38026 Grenoble cedex , France

ABSTRACT

A camera which makes use of liquid xenon in the scintillation mode is studied for Positron Emission Tomography of human brain.
A simulation which takes into account the basic physical processes only , shows that the intrinsic space resolution one can reach is $r_{min}^{FWHM} = 2.1$ mm.
Results on the performance of a Hamamatsu position sensitive PMT operating in the UV range (180 nm) are presented.

1 Introduction

The aim of the project is to develop a Positron Emission Tomograph (PET) based on the use of liquid xenon (LXe) as an active medium. This PET will be dedicated to human brain research, with a high spatial and timing resolution.

Its application for an online (^{11}C) PET camera in the context of ^{12}C hadrontherapy is also considered.
This development is proposed by three laboratories of the Joseph Fourier University of Grenoble (ISN , IRM/CHU , Nuclear Medicine department/CHU) and one industrial partner, DTA/Air Liquide, for the cryogenic equipments.
In this project, we only want to exploit the scintillation detection mode of liquid xenon. The scintillation decay time of LXe (3 ns) could result in a significant progress on the time resolution, the sensitivity and the selectivity of the detector. Benefiting from this, we believe a high image resolution ($\simeq$ 3 mm on image) and an increase by a factor 5 of the counting rate capability compared to the present tomographs could be obtained.
The execution of this project is organized along two phases : first, the development of a full PET simulation (GEANT 4 - ROOT - IDL) and a R&D investigation which includes the construction of a small prototype to confirm the project feasibility, followed by the development and the construction of a full device which could be a micro-PET camera.
We will present the operation principles of this device, its preliminary simulated performance and the first results obtained during the ongoing R&D phase.

2 Liquid xenon as compared to crystals

Liquid xenon is a known gamma detection medium which features gamma interaction properties comparable to NaI. However, its scintillation efficiency is twice as high as that of NaI , which is the most efficient inorganic crystal, and its scintillation decay time is more than ten times shorter than the best value of all crystals considered in PET development (40 ns for LSO).

An important aspect of this project is the fact that we only want to use the LXe scintillation properties [2] and not its charge collection mode [3] , because the scintillation yield when compared to the charge collection efficiency of LXe is much less sensitive to a pollution of the liquid : it may tolerate up to a few ppm of impurities (O_2...) versus a few ppb in charge mode. On top of this, the drift velocity of free electrons is much too slow.

By comparison to crystal-based cameras, the use of a liquid active medium may enable us to design novel detector geometries which could result in a sizeable amelioration of the camera performance.

The performance improvements one hopes to reach in our project, with

	LXe	LSO
τ (fast) (ns)	3 (98%)	40
τ (slow) (ns)	25 (2%)	
Photons/MeV	7.8 10^4	3.2 10^4
Wave length (nm)	178	420

Table 1: Comparison between LSO and liquid xenon as an active medium.

respect to the tomographs available today [4], are: a factor 1.5 for the axial and transaxial space resolutions ($\simeq$ 3 mm on reconstructed images with ^{18}F) , a factor 5 for the counting rate , a time coincidence window $\leq$ 5 ns (reduction of random coincidences). A good energy resolution to discriminate the scattered photons and to filter the "Compton noise" could also be obtained if one preserves a high collection efficiency of the light emitted.

3 Monte-Carlo simulation

Our simulation program is based on the GEANT4 toolkit [5]. It takes care of the complete geometrical description of the apparatus , the generation and the interaction of positons in a water standard phantom , their annihilation into photon pairs and the interaction tracking of the subsequent 511 keV photons. ROOT is used to analyze the simulation results and construct sinograms [6] which are then fed into IDL in order to build the images (using the Filtered Back-projection method).

The liquid xenon is contained in a 5 cm thick ring of 30 cm of internal radius which covers 20 cm in the axial Field Of View (FOV). The total volume of LXe is 20.5 l.

A standard phantom for simulating the conditions prevailing during a brain study is a hollow cylinder, 20 cm in length and diameter, made of a thin Plexiglas vessel filled with water. The phantom is placed at the center of the FOV in the scanner. The ^{18}F β^+ energy spectrum is sampled with the classical Von Neumann algorithm (Fig. 1).

One important physical effect which limits the PET spatial resolution is the β^+ range before it annihilates, and more precisely , the β^+ distance of flight in the human tissue (which is mainly composed of water). On figure 2 can

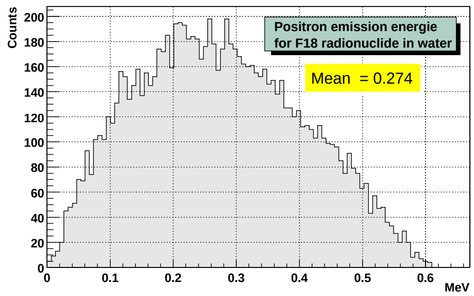

Figure 1: Simulated kinetic energy distribution of the β^+ from the ^{18}F spectrum

see that the mean distance of flight , in the case of ^{18}F, before annihilation is 0.5 mm (Fig. 2). The second physics process which has an important impact on the spatial resolution, is the acolinearity of the two annihilation γ's. This is essentially due to the orbital motion of the atomic electrons which participate to the positon annihilations [7]. The acolinearity angle can be modeled by a Gaussian distribution with a 0.25° standard deviation. The contribution of this effect , at FWHM, is 1.6 mm for our geometry.

3.1 First results

The energy deposited by the two γ in the liquid xenon was simulated. 200000 β^+ events were generated in the water phantom. The deposited energy spectrum for real (photo-electric + Compton interactions) coincidences with a threshold at 300 keV for each γ is shown in figure 3. The fraction of selected events (entering in this figure) gives the upper sensitivity (S_{max}) limit of the tomograph : $S_{max} = 1.8\%$

Only the contribution of the physical effects to the spatial resolution of the detector was simulated. Figure 4 shows the space resolution obtained (for 100000 events simulated) : 2.1 mm at FWHM, which is what we expect from the quadratic convolution of the positon distance of flight and the photon acolinearity.

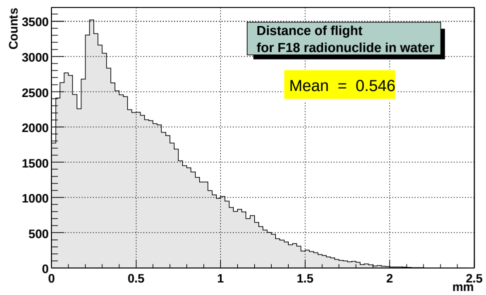

Figure 2: Simulated distribution of the β^+ distance of flight in water from the ^{18}F spectrum

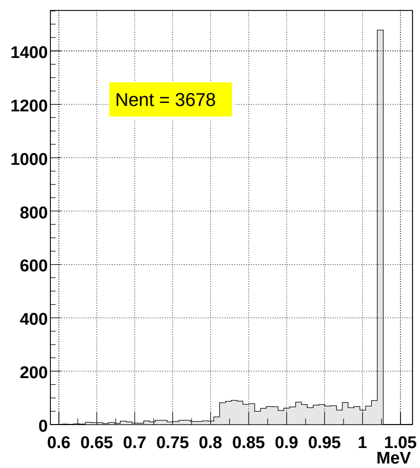

Figure 3: Simulated deposited energy spectrum for real coincidences with a threshold of 300 keV per γ

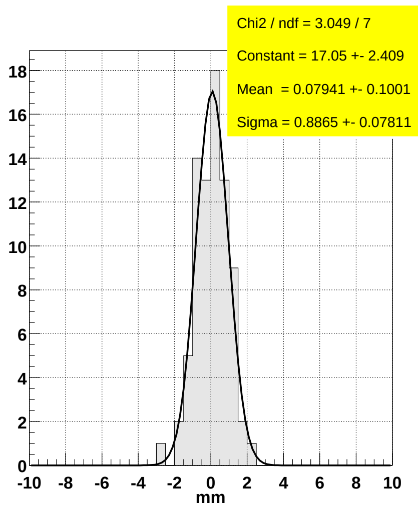

Figure 4: Space resolution for ^{18}F events simulated with a water phantom

4 R&D phase

4.1 Test of a Hamamatsu PMT

A position sensitive photo-multiplier tube, equipped with a quartz window and a RbCs photo-cathode , (HAMAMATSU R5900-00-C12) was tested with the set-up shown in figure 5. Its anode is composed of two planes of crossed plates which enable us to detect the x and y barycenters of the light pulses with a very good resolution. The primary aim of these tests is to measure the intrinsic spatial resolution of this PMT at $\lambda = 180$ nm.

The output signals from the crossed-plate anodes are amplified and undergo Analog-to-Digital Conversion (Fig. 5). Then these signals are read out by a computer for digital processing to locate the center of gravity.

The results presented in this paper were obtained at room temperature. The derived space resolution (Fig. 6) at FWHM was 0.25 mm.

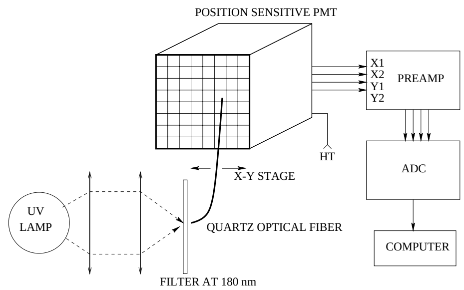

Figure 5: Schematic block diagram for position detection set-up.

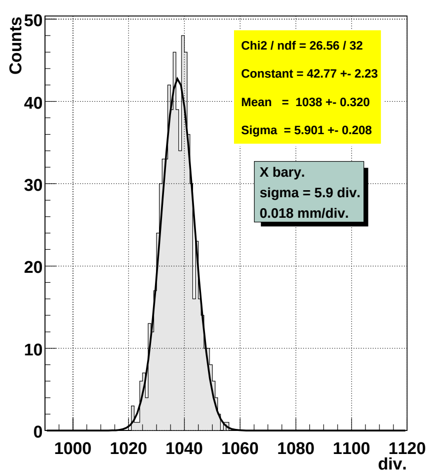

Figure 6: Spatial resolution at $\lambda = 180$ nm.

4.2 Cryogenic system

A liquid xenon cryogenic system is being built by the DTA branch of Air Liquide. It will be ready in a few weeks. We expect the first results with this system before the end of the year. It will allow us to liquefy and monitor in temperature up to 5 l of LXe. This system can be used for prototyping as well as for the construction of a small device (micro-PET camera).

5 Conclusions and perspectives

The preliminary results of a full simulation allowed us to determine the intrinsic performance of this camera . For a point-like source located at the center of the tomograph, we have shown that the intrinsic achievable space resolution is 2.1 mm.

The next step in the simulation will be to study and optimize the instrumental response of the camera so as to limit the degradation of its intrinsic space resolution as much as possible. It includes the simulation of the light collection in optical guides (Al tubes, quartz tubes...).

As a first result of our R&D activities, we may conclude that the position sensitive PMT Hamamatsu R5900 is a good candidate for the detection of light at $\lambda = 180$ nm. This has to be confirmed at the temperature of liquid xenon (165 K). In parallel, we also envisage to test Si photodiodes equipped with quartz windows.

As the test cryostat and the liquid xenon station will be shortly operational at the laboratory, we foresee to build and test a small prototype cell (2 x 2 x 3 cm^3) at the beginning of 2001, so as to confirm the instrumental performance obtained by simulation.

6 Acknowledgements

The authors would like to express their gratitude to their medical colleagues, J.F. Le Bas and D. Fagret , who by their solid support have contributed to make this project start. We address special thanks to P. de Saintignon who contributed to the design of the cryogenic equipments. We also wish to thank the technical staff of ISN and in particular : J. Ballon, J. Berger, C. Barnoux, Y. Carcagno, P. Cavalli, A. Garrigue, G. Mondin, P. Petit, P. Stassi, F. Vezzu.

This project is funded by the Rhône-Alpes regional council , IN2P3 and the Joseph Fourier University of Grenoble.

References

1. S. Nagai, M. Watanabe, H Shimoi, H. Liu and Y. Yoshizawa, "A new compact Position-Sensitive PMT for scintillation Detectors, IEEE Transactions on nuclear Science, Vol.46, NO. 3, JUNE 1999

2. F. Favata, A. Smith, M. Davdaz, T.Z. Kowalski, Nucl. Instr. and Meth. **A297** (1990) 595-601

3. V.Yu. Chepel,M.I. Lopes, A. Kuchenkov, R. Ferreira Marques, A.J.P.L. Policarpo, "Performance study of liquid xenon detector for PET", Nucl. Instr. and Meth. **A392** (1997) 427-432

4. B. Bendriem, "les détecteurs de positons : caméra PET - Caméra PET-SPECT", revue de l'ACOMEN, 1998, vol.4, n°1, p. 34

5. GEANT-detector description and simulation tool, Copyright CERN, Genève (1995)

6. D.W. Townsend, M. Defrise, "Image Reconstruction Methods in Positron Tomography", CERN 93-02

7. K.Iwata, R.G. Greaves, C.M. Surko, "γ-ray spectra from positron annihilation on atoms and molecules" Phys. Rev. A55 (1997) 3586